Pedestrian Observations
For Walkability and Good Transit, and Against Boondoggles and Pollution

Loopy Ideas Are Fine, If You're an Entrepreneur

Posted on 2013/08/13

There is a belief within American media that a successful person can succeed at anything. He (and it's invariably he) is omnicompetent, and people who question him and laugh at his outlandish ideas will invariably fail and end up working for him. If he cares about something, it's important; if he says something can be done, it can. The people who are already doing the same thing are peons and their opinions are to be discounted, since they are biased and he never is. He doesn't need to provide references or evidence – even supposedly scientific science fiction falls into this trope, in which the hero gets ideas from his gut, is always right, and never needs to do experiments.

Thus we get Hyperloop, a loopy intercity rail transit idea proposed by Tesla Motors' Elon Musk, an entrepreneur who hopes to make a living some day building cars. And thus a fair amount of the media coverage is analysis-free summary of what Tesla already said: see stenography by ABC, Forbes, the Washington Post's Wonkblog, and even BusinessWeek (which added that critics deal with "limited information"). Some media channels are more nuanced, sometimes even critical; the Wall Street Journal deserves especial credit, but Wonkblog also has a second, mildly critical post. But none has pressed Musk or Tesla about the inconsistencies in his proposal, which far exceed the obvious questions about the proposed $6 billion price tag (compare $53 billion in today's money for California HSR). For better prior criticism, see James Sinclair's post and Clem Tillier's comment on California HSR Blog.

My specific problems are that Hyperloop a) made up the cost projections, b) has awful passenger comfort, c) has very little capacity, and d) lies about energy consumption of conventional HSR. All of these come from Musk's complex in which he must reinvent everything and ignore prior work done in the field; these also raise doubts about the systems safety that he claims is impeccable.

In principle, Hyperloop is supposed to get people from Los Angeles to San Francisco in half an hour, running in a tube with near-vacuum at speeds topping at 1,220 km/h. In practice, both the costs and the running times are full of magic asterisks. The LA end is really Sylmar, at the edge of the LA Basin; with additional access time and security checks, this is no faster than conventional HSR doing the trip in 2:40. There is a crossing of the San Francisco Bay, but there's no mention of the high cost of bridging over or tunneling under the Bay – we're supposed to take it on faith the unit cost is the same as along the I-5 corridor in the Central Valley.

There is no systematic attempt at figuring out standard practices for cost, or earthquake safety (about which the report is full of FUD about the risks of a "ground-based system"). There are no references for anything; they're beneath the entrepreneur's dignity. It's fine if Musk thinks he can build certain structures for lower cost than is normal, or achieve better safety, but he should at least mention how. Instead, we get "it is expected" and "targeted" language. On Wikipedia, it would get hammered with "citation needed" and "avoid weasel words."

The worst is the cost of the civil infrastructure, the dominant term in any major transportation project's cost. Hundreds of years of incrementally-built expertise in bridge building is brushed aside with the following passage:

> *The pods and linear motors are relatively minor expenses compared to the tube itself – several hundred million dollars at most, compared with several billion dollars for the tube. Even several billion is a low number when compared with several tens of billion proposed for the track of the California rail project.*
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> *The key advantages of a tube vs. a railway track are that it can be built above the ground on pylons and it can be built in prefabricated sections that are dropped in place and joined with an orbital seam welder. By building it on pylons, you can almost entirely avoid the need to buy land by following alongside the mostly very straight California Interstate 5 highway, with only minor deviations when the highway makes a sharp turn.*

In reality, an all-elevated system is a bug rather than a feature. Central Valley land is cheap; pylons are expensive, as can be readily seen by the costs of elevated highways and trains all over the world. The unit costs for viaducts on California HSR, without overhead and management fees, are already several times as high as Musk's cost: as per PDF-page 15 of the cost overrun breakdown, unit costs for viaducts range from $50 million to $80 million per mile. Overheads and contingencies convert per-mile cost almost perfectly to per-km costs. And yet Musk thinks he can build more than 500 km of viaduct for $2.5 billion, as per PDF-page 28 of his proposal: a tenth the unit cost. The unrealistically low tunnel unit cost is at least excused on PDF-page 31 on the grounds that the tunnel diameter is low (this can also be done with trains if they're as narrow as Hyperloop, whose capsule seating is 2-abreast rather than 4- or 5-abreast as on HSR; see below on capacity). The low viaduct unit cost is not.

This alone suggests that the real cost of constructing civil infrastructure for Hyperloop is ten times as high as advertised, to say nothing of the Bay crossing. So it's the same cost as standard HSR. It's supposedly faster, but since it doesn't go all the way to Downtown Los Angeles it doesn't actually provide faster door-to-door trip times.

Nor is the system more comfortable for the passenger. Levitating systems can get away with higher cant than conventional rail because they sway less: Transrapid's lateral acceleration in the horizontal plane is about 3.6 m/s^2 in Shanghai, and the company claims 4.37 m/s^2 is possible. On standard-gauge rail, the conversion rate is approximately 150 mm of total equivalent cant per 1 m/s^2. HSR cant tops at 180-200 mm, and cant deficiency tops at 180 mm for Talgos and 270-300 mm for medium-speed Pendolinos, so about 2.5 m/s^2 at high speed; this was shown safe by simulation in Martin Lindahl's thesis, which is also a good source for track construction standards.

But Hyperloop goes one step further and proposes a lateral acceleration of 4.9 m/s^2: 0.5 g. This is after canting, according to the standards proposed:

> *The Hyperloop will be capable of traveling between Los Angeles and San Francisco in approximately 35 minutes. This requirement tends to size other portions of the system. Given the performance specification of the Hyperloop, a route has been devised to satisfy this design requirement. The Hyperloop route should be based on several considerations, including:*
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> 1. *Maintaining the tube as closely as possible to existing rights of way (e.g., following the I-5).*
> 2. *Limiting the maximum capsule speed to 760 mph (1,220 kph) for aerodynamic considerations.*
> 3. *Limiting accelerations on the passengers to 0.5g.*
> 4. *Optimizing locations of the linear motor tube sections driving the capsules.*

5. *Local geographical constraints, including location of urban areas, mountain ranges, reservoirs, national parks, roads, railroads, airports, etc. The route must respect existing structures.*

For aerodynamic efficiency, the velocity of a capsule in the Hyperloop is typically:

- *300 mph (480 kph) where local geography necessitates a tube bend radii < 1.0 mile (1.6 km)*
- *760 mph (1,220 kph) where local geography allows a tube bend > 3.0 miles (4.8 km) or where local geography permits a straight tube.*

These bend radii have been calculated so that the passenger does not experience inertial accelerations that exceed 0.5 g. This is deemed the maximum inertial acceleration that can be comfortably sustained by humans for short periods. To further reduce the inertial acceleration experienced by passengers, the capsule and/or tube will incorporate a mechanism that will allow a degree of 'banking'.

0.5 g, or 4.9 m/s^2, is extreme. Non-tilting trains do not accelerate laterally at more than 1.2 m/s^2 in the plane of the track (i.e. after accounting for cant), and at high speed they have lower lateral acceleration, about 0.67 m/s^2 with limiting cases of about 0.8 for some tilting trains relative to the plane of the train floor. For example, the Tokaido Shinkansen has 200 mm of cant and maximum speed of 255 km/h on non-tilting trains on 2,500-meter curves, for 100 mm of cant deficiency, or 0.67 m/s^2.

The proposed relationship between curve radius and speed in the Hyperloop standards is for a lateral acceleration much greater than 4.9 m/s^2 in the horizontal plane: 480 km/h at 1,600 meters is 11.1 m/s^2. This only drops to 5 m/s^2 after perfectly canting the track, converting the downward 9.8 m/s^2 gravity and the sideways acceleration into a single 14.8 m/s^2 acceleration vector downward in the plane of the capsule floor, or 5 m/s^2 more than passengers are used to. This is worse than sideways acceleration: track standards for vertical acceleration are tighter than for horizontal acceleration, about 0.5-0.67 m/s^2, one tenth to one seventh what Musk wants to subject his passengers to. It's not transportation; it's a barf ride.

Even 4.9 m/s^2 in the horizontal plane is too much. With perfect canting, it combines with gravity to accelerate passengers downward by 11 m/s^2, 1.2 m/s^2 more than the usual, twice as high as the usual standards. Motion sickness is still to be fully expected in such a case. Transrapid's 4.37 m/s^2, which adds 0.93 m/s^2 in the vertical component with perfect canting, is the limit of what's possible.

Speaking of vertical acceleration, this gets no comment at all in the Hyperloop proposal. At 1,220 km/h, it is very hard to climb grades, which would require very tall viaducts and deep tunnels under mountains. Climbing grades is easy, but vertical acceleration is such that the vertical curve radius has to be very large. A lateral acceleration of 0.67 m/s^2 would impose a minimum vertical curve radius of 170 km, versus 15 km at 360 km/h HSR speed. Changing the grade from flat to 2% would take 3.4 km, and changing back would take the same, so for climbing small hills, the effective average grade is very low (it takes 6.8 km to climb 68 meters).

Nor does jerk get any treatment. Reversing a curve takes several seconds at the cant and cant deficiency of conventional HSR (about 3 seconds by Swedish standards, more by German ones); reversing a curve with the extreme canting levels of Hyperloop would take much longer. Maintaining comfort at high total equivalent cant requires tight control of the third derivative as well as the second one; see a tilting train thesis for references.

The barf ride that is as expensive as California HSR and takes as long door-to-door is also very low-capacity. The capsules are inexplicably very short, with 28 passengers per capsule. The proposed headway is 30 seconds, for 3,360 passengers per direction per hour. A freeway lane can do better: about 2,000 vehicles, with an average intercity car occupancy of 2. HSR can do 12,000 passengers per direction per hour: 12 trains per hour is possible, and each train can easily fit 1,000 people (the Tokaido Shinkansen tops at 14 tph and 1,323 passengers per train).

But even 30 seconds appears well beyond the limit of emergency braking. It's common in gadgetbahn to propose extremely tight headways, presuming computerized control allowing vehicles to behave as if they're connected by a rod. Personal rapid transit proponents argue the same. In reality, such systems have been a subject of research for train control for quite a while now, with no positive results so far. Safety today still means safe stopping distances. If vehicles brake at a constant rate, the safe headway is half the total deceleration time; if a vehicle brakes from 1,220 km/h to zero in 60 seconds, the average acceleration is more than 5 m/s^2, twice the current regulatory safety limit for passengers with seat belts.

Most of this could be chalked to the feeling of some entrepreneurs that they must reinvent everything. The indifference to civil engineering costs, passenger comfort issues, and signal safety could all be chalked to this. So could the FUD about earthquake safety of HSR on PDF-page 5.

However, one thing could not: the chart on PDF-page 9 showing that only the Hyperloop is energy-efficient. The chart has a train consuming nearly 900 megajoules per person for an LA-San Francisco trip, about as much as a car or a plane; this is about 1,300 kJ per passenger-km. This may be true of Amtrak's diesel locomotives; but energy consumption for HSR in Spain is on average 73 Watt-hour (263 kJ) per passenger-km (see PDF-page 17 on a UIC paper on the subject of HSR carbon emissions), one fifth as much as Tesla claims. Tesla either engages in fraud or is channeling dodgy research about the electricity consumption of high-speed trains.

Indeed, a train with a thousand seats, 20 MW of power drawn, 60% seat occupancy, and a speed of 360 km/h can only ever expend 333 kJ per passenger-km while accelerating, and much less while cruising (acceleration at lower speed requires more energy per unit of distance, but cruising at lower speed expends only a fraction of the energy of full-power acceleration). Tesla's train energy consumption numbers do not pass a sanity check, which suggests either reckless disregard for the research or fraud. I wouldn't put either past Musk: the lack of references is consistent with the former, and the fact that Musk's current primary endeavor is a car company is consistent with the latter.

There is no redeeming feature of Hyperloop. Small things can possibly be fixed; the cost problems, the locations of the stations, and the passenger comfort issues given cost constraints can't. Industry insiders with ties to other speculative proposals meant to replace conventional rail, such as maglev, are in fact skeptical of Hyperloop's promises of perfect safety.

It's possible to discover something new, but people who do almost always realize the context of the discovery. If Musk really found a way to build viaducts for $5 million per kilometer, this is a huge thing for civil engineering in general and he should announce this in the most general context of urban transportation, rather than the niche of intercity transportation. If Musk has experiments showing that it's possible to have sharper turns or faster deceleration than claimed by Transrapid, then he's made a major discovery in aviation and should announce it as such. That he thinks it just applies to his project suggests he doesn't really have any real improvement.

In math, one common sanity check on a result is, "does it prove too much?" If my ten-page paper proves a result

that implies a famous open problem, then either my paper is wrong or I've proved the famous open problem, and it's up to me to take extra care to make sure I did not miss anything. Most people in this situation do this extra step and then realize that they were subtly wrong. If a famous question could be solved in ten pages, it probably wouldn't still be open. The same is even true in undergrad-level proof classes: if your homework answer proves things that are too strong, you've almost certainly made a mistake.

Musk's real sin is not the elementary mistakes; it's this lack of context. The lack of references comes from the same place, and so does the utter indifference to the unrealistically low costs. This turns it from a wrong idea that still has interesting contributions to make to a hackneyed proposal that should be dismissed and forgotten as soon as possible.

I write this not to help bury Musk; I'm not nearly famous enough to even hit a nail in his coffin. I write this to point out that, in the US, people will treat any crank seriously if he has enough money or enough prowess in another field. A sufficiently rich person is surrounded by sycophants and stenographers who won't check his numbers against anything.

There are two stories here. In the less interesting one, Musk is a modern-day streetcar conspiracy mogul: he has a car company, he hopes to make money off of it in the future and uses non-generally accepted accounting to claim he already does, and he constantly trash-talks high-speed rail, which competes with his product. Since he's not proposing to build Hyperloop soon, it could be viewed as clever distraction or FUD.

The more interesting possibility, which I am inclined toward, is that this is not fraud, or not primarily fraud. Musk is the sort of person who thinks he can wend his way from starting online companies to building cars and selling them without dealerships. I have not seen a single defense of the technical details of the proposal except for one Facebook comment that claims, doubly erroneously, that the high lateral acceleration is no problem because the tubes can be canted. Everyone, including the Facebook comment, instead gushes about Musk personally. The thinking is that he's rich, so he must always have something interesting to say; he can't be a huckster when venturing outside his field. It would be unthinkable to treat people as professionals in their own fields, who take years to make a successful sideways move and who need to be extremely careful not to make elementary mistakes. The superheros of American media coverage would instantly collapse, relegated to a specialized role while mere mortals take over most functions.

This culture of superstars is a major obstacle frustrating any attempt to improve existing technology. It more or less works for commercial websites, where the startup capital requirements are low, profits per employee are vast, and employee turnover is such that corporate culture is impossible. People get extremely rich for doing something first, even if in their absence their competitors would've done the same six months later. Valve, a video game company that recognizes this, oriented its entire structure around having no formal management at all, but for the most part what this leads to is extremely rich people like Bill Gates and Mark Zuckerberg who get treated like superstars and think they can do anything.

In infrastructure, this is not workable. Trains are 19th-century technology, as are cars and buses. Planes are from the 20th century. Companies can get extremely successful improving the technology somehow, but this works differently from the kind of entrepreneurship that's successful in the software and internet sectors. The most important airline invention since the jet engine is either the widebody (i.e. more capacity) or the suite of features that make for low-cost flights, such as quick turnarounds. What Southwest and its ultra low-cost successors have done is precious: they've figured how to trim every airline expense, from better crew utilization to incentives for lower-transaction cost booking methods. This requires perfect knowledge of preexisting practices and still takes decades to do. The growth rate of Microsoft, Google, and Facebook is not possible in

such an environment, and so the individual superstar matters far less than a positive corporate culture that can transmit itself over multiple generations of managers.

There is plenty of room for improvement in HSR technology, then, but it's of a different kind. It involves adapting techniques used by low-cost airlines to reduce costs, as SNCF is doing right now with its new low-cost TGV product. It perhaps involves controlling construction costs more tightly, though $5 million per km for viaducts seems like an impossible fantasy. But it has to come from within the business, or from someone who intimately understands the business.

And with the kind of success that US media harps on, this is almost impossible to do domestically. Someone as smart as Musk, or any of many other Silicon Valley entrepreneurs, could find a detailed breakdown of the operating and construction costs of civil infrastructure, and figure out ways of reducing them, Megabus- or Southwest-style. That's what I would do if I had the unlimited resources Musk has: I'd obtain unit costs at far greater detail than "X meters of tunnel cost $Y" and compare what New York is doing wrong that Madrid is doing right. But I don't have the resources – in money, in ability to manage people, in time. And the people who do are constantly told that they don't need to do that, that they're smart enough they can reinvent everything and that the world will bow to their greatness.

Update: people all over the Internet, including in comments below, defend the low cost projections on the grounds that the system is lighter and thinner than your average train. The proposal itself also defends the low tunneling costs on those same grounds. To see to what extent Musk takes his own idea seriously, compare the two proposals: the first for a passenger-only tube, and the second for a larger tube capable of carrying both passengers and vehicles. On PDF-pp. 25-26, the proposal states that the passenger-only tube would have an internal diameter of 2.23 meters and the passenger-plus-vehicle tube would have an internal diameter of 3.3 meters, 47% more. Despite that, the tunneling costs on PDF-p. 28 are $600 and $700 million, a difference of just 17%.

The same is true of the "but the Hyperloop capsule is lighter than a train" argument for lower pylon construction costs. Together with the differences in tube thickness posited on PDF-p. 27, 20-23 mm versus 23-25, there is 60% more tube lining in the passenger-plus-vehicle version, but the tube and pylons are projected to cost just 24% more. In this larger version, the twin tube has 0.025*3.3*pi*2 = 0.5 cubic meters of steel per meter of length, weighing about 4 tons. This ranges from a bit less than twice to a bit more than twice the weight of a train. To say nothing of the pylons' need to support their own considerable weight, which is larger than for HSR due to the need for taller viaducts coming from the constrained ability to change grade. They are far more obtrusive than trees and telephone poles, contra the claims of minimal obtrusiveness and disruption.